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The Interplanetary Magnetic Field and Magnetospheric Current Systems

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a. Generic profiles

We have performed systematic global magnetohydrodynamic (MHD) simulation studies driven by an idealized time series of solar wind parameters to establish basic cause and effect relationships between the solar wind variations and the ionosphere parameters. We studied six cases in which the interplanetary magnetic field (IMF) rotated from southward to northward in one minute. In three cases (cases A, B, and C) we ran five hours of southward IMF with $B_z = -5$ nT, followed by five hours of northward IMF with $B_z = 5$ nT. In the other three cases (cases D, E, and F) the magnetic field magnitude was increased to 10 nT. The solar wind parameters were: For cases A and D a density of 5 cm^{-3} , a thermal pressure of 3.3 nPa, and a solar wind speed 375 km/s, for cases B and E a density of 10 cm^{-3} , a thermal pressure of 9.9 nPa, and a solar wind speed 420 km/s, while for cases C and F a density of 15 cm^{-3} , a thermal pressure of 14.9 nPa, and a solar wind speed of 600 km/s.

We modeled the solar wind–magnetosphere–ionosphere system by running our global MHD simulation for each set of conditions described above until the magnetosphere came as close as possible to a steady state. Our goal in studying these particular cases is to determine “basic global” parameters that will serve as a basis for comparison to more complex solar wind conditions. Specifically, we consider how the magnitude of the IMF, the solar wind density, and the solar wind speed affect the magnetosphere ionosphere system. In particular we inter-compared the different simulations using the total power deposited into the ionosphere and the cross-polar cap potential. The main conclusions from this study is that even during steady IMF, significant variations occurred in the power deposited into the ionosphere over a period of one hour. Cases A and B showed minimal variations during southward IMF, while the remaining cases showed variations superimposed on an increasing potential. We then evaluated the formation of the current systems in different regions of the magnetotail as a function of IMF B_z . The main conclusion from this study is summarized as follows:

- Even during steady IMF, significant variations in the potential and the power occurred over a period of one hour.
- The ionospheric current response to IMF change had a time scale of about an hour regardless of the transition time.
- The potential responded to the IMF rotation in two ways. For 15 minutes after the transition there was a linear response that was stronger for shorter transitions. This was followed by a relaxation on a longer time scale.
- The field aligned current (FAC) showed a great deal of structure. This pattern was maintained during the transitions but individual features strengthened or weakened.

b. Steady Magnetospheric Convection: February 3, 1998 event

We have been studying an interval of steady magnetospheric convection on February 3, 1998 by using both spacecraft observations and a global magnetohydrodynamic simulation. Interplanetary magnetic field and solar wind plasma observations from the Wind spacecraft were used to drive a global MHD simulation of the response of the magnetosphere and ionosphere to this lengthy interval of southward IMF. During this event the WIND spacecraft was located at $x=235$, $y=3.6$, and $z=-28 R_E$ in Geocentric Solar Ecliptic Coordinates, upstream of the Earth's bow shock. At about 1235 UT, the IMF B_z turned southward and retained this southward orientation until the next day. Throughout the southward IMF interval the IMF B_x was nearly constant at 7 nT and B_y was small ($|B_y| < 4$ nT) and was directed toward dusk after 1400 UT. Prior to the southward turning a strong IMF B_y directed dawnward was present. During the southward turning large fluctuations in the IMF B_y occurred. The solar wind speed was about 325 km/s and the density was $< 4 \text{ cm}^{-3}$. At this velocity the solar wind takes about 80 minutes to flow from the Wind location ($x \approx 235 R_E$) to the magnetopause. Studies of the magnetosphere under this steady IMF condition have allowed us to directly address the basic physics of the magnetosphere. One of the questions we addressed is the relative importance of external driving and internal instability.

Data from three satellites inside the magnetosphere were available to compare to the simulation: Geotail was at $r \sim 29 R_E$ downtail in the lobe region, and the geosynchronous GOES-8 and GOES-9 satellites were located in the dayside magnetosphere. Direct comparison between these spacecraft observations and simulation results illustrate that the simulation reproduces the observed magnetic field at Geotail and at the geosynchronous satellites, indicating that we have a reasonable model of the magnetospheric configuration.

The simulation results show an unusually steady magnetospheric configuration. During the time when the IMF was northward (prior to 1406 UT) the range of the ionospheric potential was small (~ 40 kV). After the southward IMF arrived at 1406 UT the range of the potential increased substantially to > 130 kV. Afterward both the magnitude and ionospheric potential distribution remained remarkably steady for the next seven hours. The convection was characterized by a strong two-cell convection pattern that remained nearly constant. While all components of the IMF and the solar dynamic pressure vary at around 1400 UT, the strongest correlation of the potential seems to be with the IMF B_z as expected for a reconnecting magnetosphere. The cross-polar cap potential remains steady throughout the entire interval of southward IMF.

In addition to the potential we examined the energy flux into the ionosphere which is a proxy for the total auroral emission. Following the southward turning of the IMF the energy flux was enhanced and then remained steady. In agreement with auroral images from Polar satellite the simulation shows that the enhancement of the energy flux occurred on the evening side of the auroral oval, and that the auroral morning auroral emission was rotated to the evening side from midnight. The energy flux in the MHD model increased around 1400 UT, while variations were occurring in the IMF and solar wind dynamic pressure. The strongest correlation was between the slow increase of the energy flux and the IMF B_z .

c. Substorm Events

We used observations and a global MHD simulation to investigate three magnetospheric substorms that took place on November 24, 1996, July 2, 1996, and September 4, 1996. For this study we evaluated the current system that developed during substorm, cross-polar cap potential, and energy flux deposited into the ionosphere in the MHD model. During all events Geotail was in the near-Earth plasma sheet. We have modeled the three intervals by carrying out global MHD simulations. Measurements from the WIND spacecraft taken during these events were used as input to the MHD simulations.

1. November 24, 1996

Our second task was to continue looking into comparisons between spacecraft observations and simulations of a substorm that occurred on November 24, 1996. During this substorm the Geotail satellite was located $\sim 20 R_E$ downtail in the plasma sheet, while IMP 8 and Interball were in the northern lobe region. This study used observations and MHD modeling together to investigate the dynamics of the near-Earth magnetosphere. During the substorm a series of intensifications followed a long quiet period of northward IMF. The MHD simulation showed that the intensifications were associated with changes in the magnetosphere. Strong flows were seen in the observations as well as the simulation during the growth phase of the substorm.

At the beginning of the growth phase the simulation showed that reconnection was occurring tailward of Geotail at $x \sim -30 R_E$. This reconnection led to strong earthward flow at the Geotail location, which also was observed. The earthward flow in the simulation decreased and then increased as in the observations. At ~ 0819 UT, both simulations and observations showed the existence of a tailward flow. For reconnection occurring earthward of Geotail the tailward flow might be expected to occur first, followed by the earthward flow, which was not the case for this interval. Around 0837 UT the flow pattern revealed two vortices in the near-Earth plasma sheet ($x \approx -12 R_E$). This flow pattern was associated with the redirection of part of the cross-tail current to the ionosphere. During this event, reconnection started early in the growth phase. A second reconnection region developed around the time of the second intensification (0837 UT).

Our calculations showed that several current systems existed in the magnetosphere. Current systems in the magnetotail changed significantly during the substorm. Region 1 type-field-aligned currents, which flow into the equatorial region and close on the magnetopause, were enhanced during the substorm, owing to the redirection of the cross-tail current. Another current system formed solenoidal currents on the magnetopause through the plasma sheet. Yet another type of current that crossed the plasma sheet begins and ends at an IMF transition in the solar wind. At substorm onset most of the cross-tail current was redirected earthward in a narrow region near the Earth. This redirected current was diverted to the ionosphere, thereby reducing the solenoidal current. The redirection of the current around the second intensification seems to be related to a splitting of the flows into channels around two vortices.

2. September 4, 1996:

The power deposited into the ionosphere in the MHD simulation and the observed power calculated from VIS observations show large variations. However, the simulation and the observations have significant differences. The substorm onset in the MHD simulation preceded the observed onset by about 15 minutes; although the peak energies are comparable. This may be due to solar wind propagation effects and limitations in the ionospheric model. There was also a large peak in the simulated power after 2230 UT that is absent in the observations. This discrepancy is puzzling because this peak is associated with a more strongly southward IMF at 2200 UT (at the WIND locations) which should increase the power. It is interesting to note that each peak in the solar wind dynamic pressure seems to correspond to a peak in the calculated power. The main conclusion from this study is summarized as follows:

- During this day a variation in IMF B_y with a magnitude near 10 nT and with a duration of less than 10 minutes occurred.
- We have made comparisons between Geotail, Polar, Goes, IMP-8 and the MHD simulations. In general these have found to be in a reasonable agreement.
- In the simulation a strong downward IMF B_y pulse twisted the magnetotail.
- The simulation shows the existence of a large flux rope near Geotail containing both open and closed field lines.
- The change in B_y seemed to release tension in a flux rope which led to enhanced reconnection.
- A separate neutral line formed in the tail at $x \sim -30$ RE.
- There were distinct average magnetospheric states corresponding to northward or southward IMF B_z .
- The results suggest that during the interval of southward IMF the magnetosphere was responding to internal dynamics rather than being directly driven.

3. July 2, 1996:

During this event the discrete aurora typically contributes less than 15% of the power in the simulations, but after 0230 UT the discrete contribution approached the diffuse contribution. Both observations and simulations suggest that the power deposited into the ionosphere showed large variation versus time. During this whole time interval the minimum power deposited into the ionosphere was ~ 30 GW and it increased to over 100 GW during the time of enhanced activity. This is in good agreement with an empirical relationship between the AE index and the precipitated power that predicts about 100 GW for major substorms. Another feature of this interval was small scale oscillations in the solar wind dynamic pressure. We looked for a signature of these oscillations in the ionospheric parameters. The parameter that most closely followed the oscillations was the power deposited into the northern ionosphere due to the parallel plasma flow ($\int n_e k T_e V_{\parallel} ds$). This parameter may reflect ULF waves in the simulated magnetosphere. This power is only 0.1 to 0.3% of the total power deposited into the ionosphere. Each small-scale peak in the solar wind dynamic pressure evidently corresponds to a peak in the calculated power. The main conclusion from this study is summarized as follows:

- This event featured a prolonged interval of steady southward IMF (~3 hours) that slowly turned northward. A steady duskward IMF B_y also existed.
- Steady magnetospheric convection continued through most of the interval of southward IMF.
- Steady magnetospheric convection ended with substorm following the beginning of northward IMF.
- At substorm onset diffuse precipitation dropped while electron precipitation intensified.

Publications and Presentations

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